Short-Pulse Dense Wavelength-Division-Multiplexed Optical Interconnects

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**Supplementary Notes:**
DARPA/MTO, WDM for Military Platforms Workshop held in McLean, VA on April 18-19, 2000, The original document contains color images.

**Security Classification:**
- **REPORT:** unclassified
- **ABSTRACT:** unclassified
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**Limitation of Abstract:** UU

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Summary

WDM interconnects between silicon chips
  - short-pulse WDM
  - dense receiver/transmitter arrays

Synchronization with short pulses
  - data resynchronization
    - skew and jitter removal

Ultrafast optoelectronic gate
  - possible time-division demultiplexing and wavelength conversion component,
    - controllable by electronics

GaInAsN for high uniformity long-wavelength devices
  - unity sticking coefficient of N should allow high uniformity devices for long wavelengths
  - potentially usable in long wavelength WDM systems
Modulator-Based Interconnects

quantum well reflective modulators

- solder bonded to silicon integrated circuits
- can function either as photodetector or output modulator (depending on circuit)
- can be made successfully in large numbers
- can be used with short pulse sources
- can be used with WDM sources (usable range ~ 6 - 10 nm)
Quantum Well Modulator

+ve
light out
substrate (n-GaAs)

i
quantum wells (undoped)

p
bottom contact (n-AlGaAs)

top contact (p-AlGaAs)

-ve
light in
Quantum Well Modulators Solder-Bonded to Silicon Circuits - Hybrid SEED (Self Electro-optic Effect Device)

Bell Labs Multiproject OE-VLSI Wafer

Arrays of solder-bonded multiple quantum well modulator/detector diodes on 0.5 μm Si CMOS


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Baseplate Testing Setup

![Image of Baseplate Testing Setup]

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Close-up of Transmitter
Chip Details

Test receiver/transmitter circuits

PRBS generator

receiver/transmitter (two linear arrays)

channel spacing 125μm
**Example linear array optical interconnect**

**Transmitter chip**
Modulator array operating with readout beams from spot array generator

**Receiver layout**
- Photodetector
- Receiver circuit

**Receiver chip**
- Test optical readout from modulators connected to receiver circuit outputs
- Modulated optical inputs from transmitter chip
- Receiver array with
  - test output modulators
  - receiver circuits (obscured by photodetectors)
  - photodetectors

62.5 µm
Device performance

950 Mb/s modulator output with cw readout

700 Mb/s receiver eye diagram using cw laser drive (100 µW optical power per diode)
Short Pulse WDM Interconnect System

Short (e.g., 100 fs) pulse is broad band (e.g., 10 nm wavelength range) source
- spread wavelengths over reflective modulator array
- send reflected signals over single fiber to receiver array

Multiple channel interconnect with single fiber and single laser
WDM Interconnect Setup
Modulator Array Testing

Modulator array output in Optical Spectrum Analyzer System

Reflected Intensity (normalized)

\( \lambda = 846.7 \text{nm} \)

\( \lambda = 849.1 \text{nm} \)

modulator array

ch.1 ch.2 ch.3 ch.4
**Operation of WDM Interconnect**

**Entire WDM interconnect system operating at 20 Mbps**

Key issues limiting system performance

- insufficient uniformity in silicon receiver circuits
  - *improved circuits now in fabrication*

- simple bench-top optomechanics not sufficiently rigid
  - *second generation optomechanics now under construction*
Features of short-pulse dense WDM interconnects to silicon chips

- avoids electronic multiplexing and demultiplexing
- uses single laser for multiple channels
- uses single fiber for multiple channels
- intrinsically synchronizes all channels
- exploits all other advantages of short pulse interconnects
Removal of Skew By Using Short Pulses With Modulators

Effectively sampling the data on modulator

Up to one half bit of skew in modulator drive can be removed
Experimental Demonstration of Jitter Removal with Short Pulses

Demonstration of jitter removal from a single interconnect channel, at a clock rate of 82 MHz.

D. Agarwal, G. Keeler, B. Nelson, D. A. B. Miller (Stanford)
GaInAsN for Long-Wavelength Uniform Devices

Growth of this material by MBE shows

• unity sticking coefficient of nitrogen
  – *every nitrogen atom that lands on the surface incorporates, independent of growth rate*

contrasts with strong dependencies of InGaAsP growth on temperature and flux

• *may allow uniform, reproducible growth of long-wavelength devices*

Allows use of GaAs substrates

Demonstrated 1.2 micron CW VCSEL

Possibilities for other, longer wavelength devices
Phosphorus concentration ($x_p$): dependent on temperature, dependent on AsH$_3$ and PH$_3$ flux because both kinetics (incomplete pyrolysis of the hydrides) and thermodynamics determine concentration.
Bandgaps of III-V Alloys

Lattice Parameter (Å)

N causes bandgap of GaAs to decrease rapidly.

N is small and In is big ⇒ strain can be tuned from tensile to compressive when grown on GaAs.

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**GaInNAs Elemental Source MBE**

- Low substrate temperature avoids phase segregation
- Atomic Nitrogen sticking coefficient ~ 1 (N mole fraction = 1/growth rate)
- Hence expect uniform, predictable growth of this material
**CW operation oxide-confined VCSEL**

[GaInNAs oxide-confined VCSEL 0.1,0#1 CW LIV 2000 Jan 24](image1)

- **RT CW**
- **4.3µm x 4.3µm**
- **Ith = 1.45 mA**
- **0.0487 W/A**
- **Vth = 9.5 V**

[GaInNAs oxide-confined VCSEL Spectrum 2000 Jan. 24](image2)

- **CW RT**
- **4.3µm x 4.3µm**
- **1.8 Ith**
- **>45 dB**
**Ultrafast Optoelectronic Gate**

**Device concept**
- trigger top diode to give rise to temporary local voltage change in bottom diode
- voltage change in bottom diode gives temporary change in absorption, modulating beam

Optically-controlled optical gate to transfer data from one beam to another (e.g., different wavelengths)

Electrically controlled - only works when diodes are biased

**Top Diode**
- Thin intrinsic region
- $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$, transparent at $\sim850\text{nm}$

**Bottom Diode**
- Thick intrinsic region
- GaAs multiple quantum wells voltage-sensitive at $\sim850\text{nm}$
Basic Design Concept

(1) t=0

Control pulse is absorbed in top diode

(2) t=0-4ps

Due to separation of photogenerated carriers, voltage builds up, shielding the bias

(3) t~4ps

Voltage build-up changes absorption level in bottom diode: ON

(4) t=4-20ps

Voltage build-up decays away: OFF
**Diffusive Conduction**

\[
\frac{dV}{dt} = D \nabla^2_{xy} V
\]

\[
D = \frac{1}{R_{SQ} C_A}
\]

- \(R_{SQ}\) = Resistance per square
- \(C_A\) = Capacitance per unit area

**Voltage**

![Voltage Chart](chart.png)

**Graph:**
- **Radial Distance, r**
- **Voltage Change (Arb. Units)**

**Graph Details:**
- Time points: \(t=0\), 1, 4, 9
- Voltage distribution over radial distance.
Device Structure

Quantum Well Stack
(60 x 120Å GaAs)

ITO
gold
p-Al_{0.33}Ga_{0.67}As
n-Al_{0.33}Ga_{0.67}As
n-GaAs

Control
Signal
300 μm

1 μm

Bragg Mirror

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Results

Change in Relative Reflectivity

$\Delta R/R_0$

Time (ps)

Data
(1.3pJ, -8.05V, 857nm)

Theoretical Fit
(tau=3ps)
Results: Large Signal Response

Description:

- 3.5μm spot radius
- 1.5 pJ/pulse
- 39 fJ/μm²
- 2 ps pulse width

20 ps FW-10%M
30% Reflectivity Change
Nearly 2-to-1 Contrast Ratio
Results: Pulse Repetition Response

Description:
- 3.5 μm spot radius
- 20 ps pulse separation
- 2 ps pulse length
- ~ 70 fJ/pulse
**Conclusions**

- WDM interconnect between silicon chips successfully demonstrated
- Synchronization of signals using short optical pulses
- GaInAsN promising material for uniform long-wavelength devices, with cw VCSEL demonstrated
- Ultrafast optically controlled optical gate may allow fast, digital, electrically-controllable wavelength converting and switching devices